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IMAGING THE ENVIRONMENT OF A z = 6.3 SUBMILLIMETER GALAXY WITH SCUBA-2


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ABSTRACT

We describe a search for submillimeter emission in the vicinity of one of the most distant, luminous galaxies known, HerMES FLS3, at z = 6.34, exploiting it as a signpost to a potentially biased region of the early universe, as might be expected in hierarchical structure formation models. Imaging to the confusion limit with the innovative, wide-field submillimeter bolometer camera, SCUBA-2, we are sensitive to colder and/or less luminous galaxies in the surroundings of HFLS3. We use the Millennium Simulation to illustrate that HFLS3 may be expected to have companions if it is as massive as claimed, but find no significant evidence from the surface density of SCUBA-2 imaging has the potential to more tightly constrain the redshifts of nearby galaxies, at least one of which likely lies at z ≳ 5. If associations with HFLS3 can be ruled out, this could be taken as evidence that HFLS3 is less biased than a simple extrapolation of the Millennium Simulation may imply. This could suggest either that it represents a rare short-lived, but highly luminous, phase in the evolution of an otherwise typical galaxy, or that this system has suffered amplification due to a foreground gravitational lens and so is not as intrinsically luminous as claimed.

Key words: galaxies: high-redshift – galaxies: starburst – infrared: galaxies – radio continuum: galaxies – submillimeter: galaxies

Online-only material: color figures

1. INTRODUCTION

Dust extinction and a profusion of less luminous foreground galaxies makes it difficult to select high-redshift ultraluminous star-forming galaxies (LIR > 10^{12} L_\odot) at rest-frame ultraviolet/optical wavelengths. Although extinction is not an issue at radio wavelengths, an unfavorable K-correction works against detecting the highest redshift examples, z ≳ 3. Since the advent of large-format submillimeter (submm) cameras such as the Submillimeter Common-User Bolometer Array (SCUBA; Holland et al. 1999), however, it has been possible to exploit the negative K-correction in the submm waveband to select dusty, star-forming galaxies (submm-selected galaxies, or SMGs) almost independently of their redshift (e.g., Franceschini et al. 1991; Blain & Longair 1993).

The scope of this field has been substantially expanded by Herschel (Pilbratt et al. 2010), which has surveyed approximately 100 deg^2 of extragalactic sky to the confusion limit at 500 μm (as defined by Nguyen et al. 2010), with simultaneous imaging at 250 and 350 μm, using the SPIRE instrument (Griffin et al. 2010). A SPIRE image of the Spitzer First Look Survey (FLS) field, obtained as part of the Herschel Multi-Tiered Extragalactic Survey (HerMES; Oliver et al. 2012), led to the discovery of 1HERMES S350 J170647.8+584623.
2. OBSERVATIONS AND DATA REDUCTION

2.1. SCUBA-2 Imaging and Catalogs

Data were obtained simultaneously at 450 and 850 m, in 2011 September 23–24 and 2012 March 14 (project M11BGT01) using SCUBA-2 on the 15 m James Clerk Maxwell Telescope (JCMT). The observations were taken with the constant speed DAVIS pattern, which provides uniform exposure-time coverage in the central 3' diameter region of a field, and useful coverage over 12'. A total of 6.9 hr was spent integrating on HFLS3. Observing conditions were good or excellent, with precipitable water vapor levels typically 1 mm or less, corresponding to a 225 GHz optical depth of 0.05. The data were calibrated in flux density against the primary calibrators Uranus and Mars, and also secondary sources CRL 618 and CRL 2688 from the JCMT calibrator list (Dempsey et al. 2013), with estimated calibration uncertainties amounting to 5% at 850 m and 10% at 450 m.

The data were reduced using the Dynamic Iterative Map-Maker within the STARLINK SMURF package (Chapin et al. 2013) called from the ORAC-DR automated pipeline (Cavanagh et al. 2008). The chosen recipe accounted for attenuation of the signal as a result of time series filtering and removed residual low-frequency noise from the map using a jack knife method. The maps were made using inverse-variance weighting, with 1" pixels at both wavelengths, before the application of a matched filter (e.g., Chapin et al. 2011).

The map maker used a “blank-field” configuration file, optimized for faint, unresolved, or compact sources. This applies a high-pass filter with a spatial cutoff of 200", corresponding to about 0.8 Hz for a typical scanning speed of 155" s^{-1}. This removes the majority of low-frequency (large spatial scale) noise, while the remainder is removed using a Fourier-space whitening filter. This is derived from the power spectrum of the central 9" region of a jack knife map, produced from two independent halves of the total data set.

This filtering attenuates the peak signal of sources in the map. To estimate the magnitude of this effect, the pipeline re-makes each map with a fake 10 Jy Gaussian added to the raw data, offset from the nominal map center by 30" to avoid contamination by any target at the map center. The amplitude of the fake Gaussian in the output map is measured to determine a correction factor. The standard flux conversion factor, as determined from observations of primary and secondary calibrators, is then multiplied by this factor (1.17 and 1.15 at 850 and 450 m, respectively) and applied to the final image to give a map calibrated in Jy beam^{-1}. The maps with the fake Gaussian are also used to form the point-spread function (PSF) for the matched filter since they reflect the effective point-source transfer function of the map maker.

The SCUBA-2 850 and 450 m images shown in Figure 1 reach noise levels of 0.9 and 5.0 mJy beam^{-1} over the central 3' diameter regions, yielding detections of HFLS3 at approximately the 41σ and 7σ levels, respectively. At 850 m, the central 67.2 arcmin^2 of the map has a noise level of 1.5 mJy beam^{-1} or better. The astrometry of the SCUBA-2 images was found to be accurate to better than 1" by stacking at the positions of 3.6 m and 1.4 GHz sources in the field.

Following Geach et al. (2013), we create a catalog of sources from the 450 and 850 m images by searching for peaks in the beam-convolved signal-to-noise ratio (S/N) maps, recording their coordinates, flux densities, and local noise levels. We then mask a region 1.5 times the beam size and then repeat the search. Above a signal-to-noise level of 3.75, the contamination rate due to false detections is below 5%. We adopt this as our detection threshold, listing the 26 sources with 850 m flux density uncertainties below 1.5 mJy in Table 1, alongside 450 m sources selected from the same area at the same significance threshold.

We calculate our completeness levels and flux boosting following Geach et al. (2013), who followed Weiß et al. (2009), injecting 10^5 artificial point sources into a map with the same noise properties as the real image. We correct for false positives using the jack knife map.

2.2. Herschel Imaging

The acquisition and reduction of 16.8 hr of Herschel SPIRE and (shallow) PACS data for the FLS field (OD159, 164)
as part of HerMES is described in detail by Oliver et al. (2012). The SPIRE data, which are confusion-limited, are shown as a three-color image in Figure 1. The negative bowl around HFLS3 is a typical artifact of the filtering procedures employed here. The FWHM of the SCUBA-2 beams are shown as solid ellipses. Right: three-color representation of the data obtained using SPIRE at 250, 350, and 500 μm for the same field around HFLS3, superimposed with blue PACS 160 μm contours. Several of the SCUBA-2 850 μm sources are associated with green SPIRE sources — those with SEDs peaking at 350 μm, consistent with z ≈ 2; others have no obvious SPIRE counterparts and may lie at considerably higher redshifts. The region over which PACS sensitivity is better than half the best is outlined in blue. Positions of faint 1.4 GHz sources from the ~1.3” resolution, σ ∼ 11 μJy beam⁻¹ Karl G. Jansky Very Large Array imaging described in Riechers et al. (2013) are marked with “+” (the radio catalog covers only ≈25% of the region shown, hence the detection rate is unremarkable). North is up and east is to the left; offsets from α2000 = 17:06:47.8, δ2000 = +58:46:23 are marked. (A color version of this figure is available in the online journal.)

Figure 1. Left: SCUBA-2 imaging at 850 μm, with 450 and 850 μm sources marked by red squares and white circles, respectively, for the 67.2 arcmin² where σ850 ≤ 1.5 mJy beam⁻¹. The negative bowl around HFLS3 is a typical artifact of the filtering procedures employed here. The FWHM of the SCUBA-2 beams are shown as solid ellipses. Right: three-color representation of the data obtained using SPIRE at 250, 350, and 500 μm for the same field around HFLS3, superimposed with blue PACS 160 μm contours. Several of the SCUBA-2 850 μm sources are associated with green SPIRE sources — those with SEDs peaking at 350 μm, consistent with z ≈ 2; others have no obvious SPIRE counterparts and may lie at considerably higher redshifts. The region over which PACS sensitivity is better than half the best is outlined in blue. Positions of faint 1.4 GHz sources from the ~1.3” resolution, σ ∼ 11 μJy beam⁻¹ Karl G. Jansky Very Large Array imaging described in Riechers et al. (2013) are marked with “+” (the radio catalog covers only ≈25% of the region shown, hence the detection rate is unremarkable). North is up and east is to the left; offsets from α2000 = 17:06:47.8, δ2000 = +58:46:23 are marked. (A color version of this figure is available in the online journal.)

We have obtained much deeper data from PACS (Poglitsch et al. 2010) via a 3.9 hr integration as part of program OT2_DRIECHER_3 (OD1329; see Riechers et al. 2013, for further details). Observations were carried out on 2013 January 1 in mini-scan mapping mode (4 x 15 repeats), using the 70 plus 160 μm parallel mode and the 110 plus 160 μm parallel mode for one orthogonal cross-scan pair each. In the 70, 110, and 160 μm bands, the rms sensitivities at the position of HFLS3 are 0.67, 0.73, and 1.35 mJy beam⁻¹, respectively. Data reduction and mosaicking were carried out using standard procedures. The absolute flux density scale is accurate to 5%. The 160 μm PACS image, the only one potentially useful in the context of faint, distant galaxies, is shown in Figure 1.

The 250, 350, and 500 μm flux densities, S250, S350, and S500, at the positions25 of the 19 SMGs discussed in Section 2.1 were determined using beam-convolved SPIRE maps. None of our SMGs lie near bright SPIRE sources so we expect the uncertainties associated with these flux densities should be close to the typical confusion levels, ≈6 mJy (where, hereafter, we adopt σconf in each SPIRE band from Nguyen et al. 2010).

3. RESULTS, ANALYSIS, AND DISCUSSION

HFLS3 dominates the submm sky in the 67.2 arcmin² (8 Mpc²) region we have mapped at 850 μm with SCUBA-2, being three times brighter than the next brightest submm emitter (Figure 1; Table 1). At 450 μm, HFLS3 is the brightest SMG in the region, despite the peak of its SED having moved beyond that filter; it is one of two sources detected formally at both 450 and 850 μm. Perhaps unsurprisingly, there are no sources in common between the SCUBA-2 and PACS images.

We see no evidence for an overdensity of SMGs on <1.5 Mpc scales around the position of HFLS3 in either our 450 or 850 μm maps (Figure 1).

3.1. Number Counts Relative to Blank Fields

Although no obvious cluster of submm emitters is visible near HFLS3 in Figure 1, we must ask whether the entire 8 Mpc² field might be overdense in SMGs. Figure 2 shows the density of sources brighter than S₅, at 450 and 850 μm — extracted at the 3.75σ level and corrected for incompleteness using the analysis discussed in Section 2.1, excluding HFLS3 itself — relative to the source density seen in typical blank-field surveys, where the same techniques have been used to construct catalogs and correct for incompleteness (Coppin et al. 2006; Geach et al. 2013). The only hint of an overdensity comes in the 850 μm data, where, hereafter, we adopt σconf in each SPIRE band from Nguyen et al. 2010).

25 Positions are known to σpos ≈ 2” even for the least significant SMGs, a small fraction of the beam-convolved SPIRE PSF.
Table 1  
Sources Detected at 850 and 450 μm Near HFLS3

<table>
<thead>
<tr>
<th>IAU Name</th>
<th>S (mJy)</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>850 μm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2FLS850 J170647.67+584623.0a</td>
<td>35.4 ± 0.9</td>
<td>40.9</td>
</tr>
<tr>
<td>S2FLS850 J170631.07+584812.9</td>
<td>11.4 ± 1.3</td>
<td>8.6</td>
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<tr>
<td>S2FLS850 J170621.93+584826.8</td>
<td>9.3 ± 1.4</td>
<td>6.5</td>
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<tr>
<td>S2FLS850 J170646.64+584816.0</td>
<td>5.6 ± 1.0</td>
<td>5.5</td>
</tr>
<tr>
<td>S2FLS850 J170647.80+584735.0</td>
<td>4.9 ± 0.9</td>
<td>5.3</td>
</tr>
<tr>
<td>S2FLS850 J170701.41+584318.0</td>
<td>7.5 ± 1.4</td>
<td>5.3</td>
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<tr>
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<td>4.7 ± 1.0</td>
<td>4.6</td>
</tr>
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<td>5.8 ± 1.3</td>
<td>4.6</td>
</tr>
<tr>
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<td>5.6 ± 1.2</td>
<td>4.6</td>
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<tr>
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<td>6.1 ± 1.4</td>
<td>4.5</td>
</tr>
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<td>6.2 ± 1.4</td>
<td>4.4</td>
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<td>4.2</td>
</tr>
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<td>5.5 ± 1.3</td>
<td>4.2</td>
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<td>4.2</td>
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<td>4.2</td>
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<td>3.9</td>
</tr>
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<td>3.8</td>
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<td>3.3 ± 0.9</td>
<td>3.8</td>
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<tr>
<td><strong>450 μm</strong></td>
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<td></td>
</tr>
<tr>
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<td>39.8 ± 5.5</td>
<td>7.3</td>
</tr>
<tr>
<td>S2FLS450 J170701.05+584715.0</td>
<td>29.4 ± 6.9</td>
<td>4.3</td>
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<tr>
<td>S2FLS450 J170701.33+584813.9</td>
<td>36.3 ± 8.8</td>
<td>4.1</td>
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<td>32.5 ± 8.3</td>
<td>3.9</td>
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<tr>
<td>S2FLS450 J170658.59+584419.0</td>
<td>30.2 ± 7.8</td>
<td>3.9</td>
</tr>
<tr>
<td>S2FLS450 J170711.99+584734.9</td>
<td>34.5 ± 8.9</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Notes.  
a Deboosted flux densities; errors exclude 5% and 10% calibration uncertainties at 850 and 450 μm, respectively.  
b HFLS3.

megaparsec scales at flux densities above the JCMT confusion limit.

3.2. Redshift Constraints for Sources in the Field

The $K$-correction in the submm waveband means our SCUBA-2 maps are sensitive to SMGs across a very wide redshift range, reducing the contrast of any potential structure around HFLS3. However, with SCUBA-2, SPIRE, and PACS photometry in hand, we are able to crudely constrain the likely redshifts of the galaxies detected in the field surrounding HFLS3, using their far-IR/submm colors. Figure 3 shows color–color plots for HFLS3 and its neighboring SMGs, designed to exploit information from SCUBA-2 at 850 μm to constrain the redshifts of galaxies at $z > 2$ (Ivison et al. 2012), probing their colors across the rest-frame $\approx 100$ μm bump seen in the SEDs of all dusty, star-forming galaxies. The colored backgrounds in the upper and lower panels of Figure 3 indicate the typical redshift of the subset of 107 model SEDs that fall in each pixel, where we have adopted a flat redshift distribution ($z = 0–7$), a flat distribution for the spectral dependence of the dust emissivity ($\beta = 1.8–2.0$), centered on the $\beta$ measured for HFLS3), and 10% flux density uncertainties. For the upper panel of Figure 3, we adopt the dust temperature of HFLS3 ($T_d = 56$ K).

We concentrate only on those galaxies detected by SCUBA-2, since SPIRE-detected galaxy with a typical SED in the vicinity of HFLS3 could not have evaded detection at 850 μm. Despite its relatively high $T_d$, HFLS3 is the reddest source detected in the three bands used to make Figure 3.

For SMGs with SPIRE flux densities below 2$\sigma_{\text{conf}}$, we plot limits based on the measured flux density (zero, if negative) plus $\sigma_{\text{conf}}$. We have arbitrarily placed those sources without detections at 350 and 500 μm at $S_{350}/S_{500} = 2$; some could be considerably redder than this in $S_{350}/S_{500}$, but we cannot constrain this color reliably with the relatively shallow Herschel data at our disposal. Several SMGs may also be as red as HFLS3 in $S_{350}/S_{500}$, perhaps redder. One particularly interesting example is S2FLS850 J170647.80+584735.0, a 5.3σ SCUBA-2 source with no significant SPIRE emission. With $S_{500}/S_{350} > 0.9$, this SMG likely lies at $z > 5$, with a lower $T_d$ and luminosity than HFLS3.

The lower panel of Figure 3 shows the effect of lowering $T_d$, illustrating an issue long known to hamper studies of this kind: far-IR/submm colors are sensitive only to $(1 + z)/T_d$ (Blain 1999), i.e., redshift and $T_d$ are degenerate. As a result, our current data does not allow us to conclude with certainty that the environment surrounding HFLS3 contains other luminous, dusty starbursts; however, we can neither rule it out.

Single-dish imaging of this field at 450, 850, 1100, and 2000 μm is possible from the ground, reaching $\sigma_{450} \sim 2.5$ mJy and $\sigma_{2000} \sim 0.1$ mJy over tens of square arcminutes with existing facilities in a few tens of hours. Would these data be capable

![Figure 2](image_url)
of further constraining the redshifts of the SMGs discovered here? Figure 4 shows $S_{350}/S_{850}$ versus $S_{2000}/S_{850}$ and we see that the latter color offers little insight. For $S_{850}/S_{450} \lesssim 0.3$, we can rule out $z \gtrsim 2$ for all but the warmest dust; $S_{850}/S_{850} \gtrsim 1$ suggests $z \gtrsim 5$, with dust much cooler than 35 K unlikely at these redshifts; $S_{2000}/S_{850}$ offers less insight.

(A color version of this figure is available in the online journal.)

3.3. Predictions from the Millennium Simulation

Is the field surrounding HFLS3 less overdense in submm sources than expected for such a massive galaxy living in a biased environment at high redshift, similar to those found around high-redshift radio galaxies and radio-loud quasars at $z = 2–4$ (e.g., Stevens et al. 2003, 2004)? The answer to this question may have implications for the potential gravitational amplification suffered by HFLS3 (see Section 1) or for investigating the potential presence of a buried AGN and its role in supporting its high-IR luminosity.

By necessity this comparison will be crude. We therefore selected the implementation of the Bower et al. (2006) galaxy-formation recipe in the Millennium Simulation (Springel et al. 2005) and searched the $z = 6.2$ output for galaxies with a total baryonic mass in excess of $1.3 \times 10^{11} M_\odot$, consistent with the combined mass of gas and stars estimated for HFLS3 (Riechers et al. 2013). By adopting a total baryonic mass cut, we are less sensitive to details of the early star-formation histories of galaxies in the model.

We find just one galaxy in the $3.2 \times 10^8$ Mpc$^3$ volume at $z = 6.2$ with a total baryonic mass above $1.3 \times 10^{11} M_\odot$. All its baryonic mass is in stars; it hosts a $2 \times 10^8 M_\odot$ black hole and is the central galaxy of a $6 \times 10^{12} M_\odot$ halo, four times more massive than the next most massive galaxy’s halo within the volume, and
the optimal environment to find merging galaxies according to the simulations of Hopkins et al. (2008). Another 16 galaxies are spread across a ≈ 0.7 comoving Mpc diameter region around the most massive galaxy, but most of these are dwarf galaxies with baryonic masses, \( \lesssim 10^9 M_\odot \). Inside a sphere with an angular size of 9′ diameter, centered on the 1.3 × 10^{11} M_\odot galaxy, only two galaxies have total baryonic masses of \( \gtrsim 15\% \) of the mass of HFLS3 (we choose this limit as the faintest submm emitters in this field have 850\( \mu \)m flux densities of around 15\% that of HFLS3); the next most massive galaxy has half this mass. The total masses of these two companion galaxies in stars and gas are approximately 3 and 4 \times 10^{10} M_\odot and their predicted \( K_{\text{Vega}} \) magnitudes are 23.5 and 25.0. The HFLS3 clone is predicted to have \( K_{\text{Vega}} = 22.5 \) for a distance modulus of 49.0, about a magnitude fainter than observed.

From this simple theoretical comparison, we thus expect 2±2 detectable galaxies in the vicinity of HFLS3 if, as expected, their starburst lifetimes are a significant fraction of the time available at this early epoch. This is consistent with the fact that some high-redshift SMGs do have submm-bright companions (e.g., GN 20; Daddi et al. 2009) while others have Lyman-break galaxies nearby but no submm-bright companions (e.g., AzTEC-3; Capak et al. 2011).

Having found no clear evidence for or against the level of overdensity expected in simulations, we can draw no strong conclusions regarding the likely gravitational amplification suffered by HFLS3, or for the likely fraction of its luminosity provided by a buried AGN.

4. CONCLUSIONS

We have detected the most distant, dusty starburst galaxy, HFLS3, at high significance with SCUBA-2. We detect another 29 dusty galaxies within an area of 67.2 arcmin2 surrounding HFLS3, most of them likely at lower redshift. We find no compelling evidence, from surface density or color, for an overdensity of SMGs around HFLS3, although applying similar selection criteria to theoretical models suggests that a modest excess could be expected, as is found for some other high-redshift SMGs (e.g., GN 20; Daddi et al. 2009). We can therefore draw no strong conclusions regarding the likely gravitational amplification suffered by HFLS3, or for the likely fraction of its luminosity provided by a buried AGN.

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Facilities: JCMT, Herschel

REFERENCES

Blain, A. W. 1999, MNJAS, 309, 955
Blain, A. W., & Longair, M. S. 1993, MNJAS, 264, 509
Dempsey, J. T., Friberg, P., Jennss, T., et al. 2013, MNJAS, 430, 2534
Geach, J. E., Chapin, E. L., Coppin, K. E. K., et al. 2013, MNJAS, 432, 53
Holland, W. S., Bintley, D., Chapin, E. L., et al. 2013, MNJAS, 430, 2513
Holland, W. S., Robson, E. I., Gear, W. K., et al. 1999, MNJAS, 303, 659
Ivison, R. J., Smail, I., Ambland, A., et al. 2012, MNJAS, 425, 1320
Jennss, T., Robson, E. I., & Stevens, J. A. 2010, MNJAS, 401, 1240
Priddle, R. S., Ivison, R. J., & Isaak, K. G. 2008, MNJAS, 383, 289
Swinbank, A. M., Simpson, J. M., Smail, I., et al. 2014, MNJAS, 438, 1267